Cryogenic Refrigerators-
an Updated Survey
The National Bureau of Standards was established by an act of Congress March 3, 1901. The Bureau's overall goal is to strengthen and advance the Nation's science and technology and facilitate their effective application for public benefit. To this end, the Bureau conducts research and provides: (1) a basis for the Nation's physical measurement system, (2) scientific and technological services for industry and government, (3) a technical basis for equity in trade, and (4) technical services to promote public safety. The Bureau consists of the Institute for Basic Standards, the Institute for Materials Research, the Institute for Applied Technology, the Institute for Computer Sciences and Technology, and the Office for Information Programs.

**THE INSTITUTE FOR BASIC STANDARDS** provides the central basis within the United States of a complete and consistent system of physical measurement; coordinates that system with measurement systems of other nations; and furnishes essential services leading to accurate and uniform physical measurements throughout the Nation's scientific community, industry, and commerce. The Institute consists of a Center for Radiation Research, an Office of Measurement Services and the following divisions:

- Applied Mathematics — Electricity — Mechanics — Heat — Optical Physics — Nuclear Sciences
- Applied Radiation — Quantum Electronics — Electromagnetics — Time and Frequency
- Laboratory Astrophysics — Cryogenics.

**THE INSTITUTE FOR MATERIALS RESEARCH** conducts materials research leading to improved methods of measurement, standards, and data on the properties of well-characterized materials needed by industry, commerce, educational institutions, and Government; provides advisory and research services to other Government agencies; and develops, produces, and distributes standard reference materials. The Institute consists of the Office of Standard Reference Materials and the following divisions:


**THE INSTITUTE FOR APPLIED TECHNOLOGY** provides technical services to promote the use of available technology and to facilitate technological innovation in industry and Government; cooperates with public and private organizations leading to the development of technological standards (including mandatory safety standards), codes and methods of test; and provides technical advice and services to Government agencies upon request. The Institute consists of a Center for Building Technology and the following divisions and offices:


**THE INSTITUTE FOR COMPUTER SCIENCES AND TECHNOLOGY** conducts research and provides technical services designed to aid Government agencies in improving cost effectiveness in the conduct of their programs through the selection, acquisition, and effective utilization of automatic data processing equipment; and serves as the principal focus within the executive branch for the development of Federal standards for automatic data processing equipment, techniques, and computer languages. The Institute consists of the following divisions:

- Computer Services — Systems and Software — Computer Systems Engineering — Information Technology.

**THE OFFICE FOR INFORMATION PROGRAMS** promotes optimum dissemination and accessibility of scientific information generated within NBS and other agencies of the Federal Government; promotes the development of the National Standard Reference Data System and a system of information analysis centers dealing with the broader aspects of the National Measurement System; provides appropriate services to ensure that the NBS staff has optimum accessibility to the scientific information of the world. The Office consists of the following organizational units:


---

1 Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D.C. 20234.
2 Part of the Center for Radiation Research.
3 Located at Boulder, Colorado 80302.
4 Part of the Center for Building Technology.
Cryogenic Refrigerators -
An Updated Survey

T. R. Strobridge

Cryogenics Division
Institute for Basic Standards
National Bureau of Standards
Boulder, Colorado 80302

Technical note no. 655

U.S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director
Issued June 1974
Cryogenic Refrigerators - An Updated Survey

T. R. Strobridge

In 1969, we gave efficiency, weight, volume, and cost data for 95 cryogenic refrigerators and liquefiers excluding air separation plants. Recently, the survey was repeated. The original data and those for 49 additional refrigerators and liquefiers are presented spanning refrigeration capacities from 0.2 to 10^6 W and temperatures from 1.85 to 90 K. Generally, there is no change in the trends exhibited by the older data except that the high temperature, low capacity new units seem to be larger, heavier and slightly less efficient than in prior years. Presumably, these effects are due to efforts to increase useful life and reliability. Costs remain the same as predicted before even though no dollar value adjustments were made.

Key words: Cost; cryogenic refrigerators; efficiency; volume; weight.

Late in 1968, we started collecting data on the efficiency, weight, volume, and cost of cryogenic refrigerators and liquefiers excluding air separation plants. The data on 95 units from the U. S. and Europe were presented in early 1969 [1]. There has been sufficient continuing interest shown so that the survey has been updated. Information on 49 other refrigerators and liquefiers is presented here along with the original data and portions of the original text.

Although there is considerable scatter in the data, significant trends can be identified that yield values useful for estimating purposes. The efficiency data show the amount of input power required by a refrigerator and thus give one part of the operating expense. The mass of a unit may not be of concern to an accelerator designer interested in large units, but it can be important in the applications calling for low cooling capacity aboard spacecraft or airplanes. Space occupied by the refrigerator can
be important, especially in the premium areas near accelerators, in experimental halls, in spacecraft and airplanes or on ships. The interest in capital cost is obvious since this type of machinery is not inexpensive. In all of the charts which follow, lines have been drawn through the data which represent the author's judgment of an average and are thus subject to arbitration. The general shape of the curves can be predicted from a knowledge of the characteristics of low temperature refrigerators, but since there is wide variation in the data any quantitative interpretation must be approached with caution.

Through the second law of thermodynamics, the minimum power required to produce a unit of refrigeration under ideal conditions is given by

\[
\frac{W}{Q} \text{Carnot} = \frac{T_o - T}{T},
\]

(1)

where \(W_c\) is the net input power required (power for compression minus the power produced by expanders if any), \(Q\) is the refrigeration produced, \(T_o\) is the temperature of the surroundings, nominally 300 K, and \(T\) is the desired refrigeration temperature. As \(T\) becomes smaller, the specific power requirement increases rapidly as seen in table 1 which also gives the ideal power requirement for liquefaction. \(T\) in table 1 is taken to be the normal boiling temperature of the fluids.

The difference in input power required to cool an object with liquid produced by a liquefier or with a continuously operating refrigerator is evident. More power is required by a liquefier because when the liquid is evaporated at another location, the cold effluent vapor cannot be used in the liquefaction process to help cool the feed gas stream. An ideal helium liquefier would require a power input of 236 W to produce liquid
at the rate of 1 liter per hour. The heat of vaporization of helium is low and 1 W will evaporate 1.38 liters per hour. Therefore, 326 W would be required to power a liquefier whose liquid product was used to absorb a 1 W heat load at 4.2 K. An ideal refrigerator would require 70.4 W input power to produce 1 W of refrigeration at the same temperature level. This difference in power requirement does not mean that a refrigerator should be chosen over a liquefier for all cooling applications; there are conceivable circumstances in which a liquefier would be the better choice.

<table>
<thead>
<tr>
<th>Fluid</th>
<th>T (K)</th>
<th>Refrigeration (W/W)</th>
<th>Liquefaction (Whr/liter)</th>
<th>Evaporating Liquid Refrigeration* (W/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium</td>
<td>4.2</td>
<td>70.4</td>
<td>236</td>
<td>326</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>20.4</td>
<td>13.7</td>
<td>278</td>
<td>31.7</td>
</tr>
<tr>
<td>Neon</td>
<td>27.1</td>
<td>10.1</td>
<td>447</td>
<td>15.5</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>77.4</td>
<td>2.88</td>
<td>173</td>
<td>3.87</td>
</tr>
<tr>
<td>Fluorine</td>
<td>85.0</td>
<td>2.53</td>
<td>238</td>
<td>3.26</td>
</tr>
<tr>
<td>Argon</td>
<td>87.3</td>
<td>2.44</td>
<td>185</td>
<td>2.95</td>
</tr>
<tr>
<td>Oxygen</td>
<td>90.2</td>
<td>2.33</td>
<td>195</td>
<td>2.89</td>
</tr>
<tr>
<td>Methane</td>
<td>111.5</td>
<td>1.69</td>
<td>129</td>
<td>2.15</td>
</tr>
</tbody>
</table>

* Obtained by dividing the ideal liquefaction power requirement by the heat of vaporization of the fluid.
When comparing the efficiencies of low temperature refrigerators, it is informative to examine the ratio

$$\text{Percent Carnot} = \frac{\left(\frac{W_c}{Q}\right)_{\text{Carnot}}}{\left(\frac{W_c}{Q}\right)_{\text{Actual}}} \times 100.$$  \hspace{1cm} (2)

This ratio indicates the extent to which the actual refrigerator deviates from ideal performance. The same ratio is formed for liquefiers using the values from table 1 and the actual power consumption per liter per hour. The capacity of the liquefiers included in the data has been converted to equivalent refrigeration capacity by determining the percent of Carnot performance that they achieve as liquefiers and then calculating the refrigeration output of a refrigerator operating at the same efficiency with the same input power. In some instances equivalent refrigeration capacity was given by the manufacturers and was used directly. In all instances, the input power was taken as the installed drive power, not the power measured at the input to the drive motor.

In figure 1, the percent of Carnot given by eq (2) is plotted as a function of refrigeration capacity in watts. The largest of the new units in the 1.8 to 9 K temperature range is a proposed liquefier. Actually, the liquefier is now operating at reduced capacity (the equivalent of 3420 W) but is designed for the greater capacity at higher flow rates. The original curve is unchanged as the new data show no significant different trend.

Historically, the contention has been that higher temperature refrigerators (or liquefiers) are more efficient. The data for refrigeration temperatures between 10 and 30 K (and 30 to 90 K) refute that notion.
Figure 1. Efficiency of low temperature refrigerators and liquefiers as a function of refrigeration capacity.
at least when presented on this common basis. To be sure, less input power is required to produce the same number of watts of cooling at higher temperatures, but the losses relative to ideal are proportionally the same. For many of the refrigerators of less than 10 kW capacity, liquid nitrogen precooling consumption rates are available, but the equivalent power that would be consumed if the precooling were provided by a closed cycle refrigerator on site has not been included in the efficiency computation. Therefore, the efficiencies of a number of the units would be slightly lower than shown if this factor were included. The largest of the units shown are high capacity hydrogen liquefiers. Here nitrogen temperature precooling is commonly provided by closed cycle nitrogen refrigerators and the input power requirements are known and have been included. This means that the values are more nearly true and are not slightly biased as are some of those at lower capacities.

Performance data for higher temperature plants, in the 30 - 90 K range, are not as numerous but the trend is obvious. In the 10 to 1000 W range, indeed efficiencies are higher, but the estimate given by a supplier of large facilities (shown at the right as off scale) is comparable to lower temperature plants. At lower capacities, the deviation in performance is an entire decade. It must be noted that these are units of very low input power and it is not surprising to find such variation. In spite of the scatter in the data, it is clear that very small low temperature refrigerators are subject to proportionally higher losses than the larger units.

Many of the low capacity refrigerators have been intended for military or space flight missions. Emphasis was necessarily placed on light, small sized machines. Many of the refrigerators in the original survey (1.8 - 9 K) are shown smaller and lighter than the average at that time, figures 2 and 3. This trend has continued. Data recently collected for the 30 to 90 K temperature range, however, show that
Figure 2. Volume of low temperature refrigerators and liquefiers as a function of refrigeration capacity.
Figure 3. Mass of low temperature refrigerators and liquefiers as a function of refrigeration capacity.
many of the new low capacity units are heavier and larger than the older refrigerators. Many of these new machines use thermodynamic cycles that have not been common in the past. It may be that the demonstrated weight and volume increases are caused by lack of refinement with the new cycles; or it may be that larger heavier structures have been necessary to reach required machine lifetime levels and/or lower costs.

Some time ago the line shown in figure 4 was established for 4 K refrigerators with only a few points. The curve adequately represents subsequent additions of data. Notice that the abscissa is now input power, not refrigeration capacity. The input power at any refrigeration capacity can be determined from the efficiency data. The cost of many classes of machinery is proportional to the 0.7 power of the installed input power. Hydrogen temperature units and even higher temperature refrigerators and liquefiers follow the trend quite well. These data indicate that to a first approximation for refrigerators and liquefiers operating in the range 1.8 to 90 K,

$$C = 6000 P^{0.7},$$  \hspace{1cm} (3)

where C is the cost in dollars and P is the installed input power in kilowatts. Adjustments have not been made for the change in value of the dollar since the data are so scattered.

The several million dollar units in the upper right are typical of large hydrogen liquefiers; here the costs are hard to define because in some instances, the equipment for producing hydrogen feed gas is included in the cost figures. Again, it is emphasized that the charts are intended for estimating purposes only.

Existing low temperature refrigerators cover a wide range of capacity and temperatures and the performance (input power) can be fairly well predicted. It does not appear that any significant increase
Figure 4. Cost of low temperature refrigerators and liquefiers as a function of installed input power.
in efficiency has been achieved for the entire class of devices in the past few years although in certain instances good performance has been realized. The more efficient facilities are in the large sizes and use complex thermodynamic cycles. Perhaps the same performance potential exists in smaller units, but costs might be prohibitive and the savings in electrical power would not justify the greater capital outlay. The trends are identifiable in the mass and volume characteristics and there is the potential for reducing both, perhaps with an increase in price. Capital cost should be predictable for standard types of refrigerators at least. Experience shows that special requirements are expensive but the field is quite competitive as indicated by the twenty-one European prices which are included.

Acknowledgements

The author wishes to acknowledge the information and assistance contributed by the following persons in private communications used to update this survey:


Reference

Cryogenic Refrigerators - An Updated Survey

In 1969, we gave efficiency, weight, volume, and cost data for 95 cryogenic refrigerators and liquefiers excluding air separation plants. Recently, the survey was repeated. The original data and those for 49 additional refrigerators and liquefiers are presented spanning refrigeration capacities from 0.2 to $10^6$ W and temperatures from 1.85 to 90 K. Generally, there is no change in the trends exhibited by the older data except that the high temperature, low capacity new units seem to be larger, heavier and slightly less efficient than in prior years. Presumably, these effects are due to efforts to increase useful life and reliability. Costs remain the same as predicted before even though no dollar value adjustments were made.

Cost; cryogenic refrigerators; efficiency; volume; weight.
NBS TECHNICAL PUBLICATIONS

PERIODICALS

JOURNAL OF RESEARCH reports National Bureau of Standards research and development in physics, mathematics, and chemistry. Comprehensive scientific papers give complete details of the work, including laboratory data, experimental procedures, and theoretical and mathematical analyses. Illustrated with photographs, drawings, and charts. Includes listings of other NBS papers as issued.

Published in two sections, available separately:

- Physics and Chemistry (Section A)

Papers of interest primarily to scientists working in these fields. This section covers a broad range of physical and chemical research, with major emphasis on standards of physical measurement, fundamental constants, and properties of matter. Issued six times a year. Annual subscription: Domestic, $17.00; Foreign, $21.25.

- Mathematical Sciences (Section B)

Studies and compilations designed mainly for the mathematician and theoretical physicist. Topics in mathematical statistics, theory of experiment design, numerical analysis, theoretical physics and chemistry, logical design and programming of computers and computer systems. Short numerical tables. Issued quarterly. Annual subscription: Domestic, $9.00; Foreign, $11.25.

DIMENSIONS, NBS

The best single source of information concerning the Bureau's measurement, research, developmental, cooperative, and publication activities, this monthly publication is designed for the layman and also for the industry-oriented individual whose daily work involves intimate contact with science and technology—for engineers, chemists, physicists, research managers, product-development managers, and company executives. Annual subscription: Domestic, $6.50; Foreign, $8.25.

BIBLIOGRAPHIC SUBSCRIPTION SERVICES

The following current-awareness and literature-survey bibliographies are issued periodically by the Bureau:

Cryogenic Data Center Current Awareness Service (Publications and Reports of Interest in Cryogenics). A literature survey issued weekly. Annual subscription: Domestic, $20.00; Foreign, $25.00.


Send subscription orders and remittances for the preceding bibliographic services to the U.S. Department of Commerce, National Technical Information Service, Springfield, Va. 22151.


NONPERIODICALS

Applied Mathematics Series. Mathematical tables, manuals, and studies.


Handbooks. Recommended codes of engineering and industrial practice (including safety codes) developed in cooperation with interested industries, professional organizations, and regulatory bodies.

Special Publications. Proceedings of NBS conferences, bibliographies, annual reports, wall charts, pamphlets, etc.

Monographs. Major contributions to the technical literature on various subjects related to the Bureau's scientific and technical activities.

National Standard Reference Data Series. NSRDS provides quantitative data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated.

Product Standards. Provide requirements for sizes, types, quality, and methods for testing various industrial products. These standards are developed cooperatively with interested Government and industry groups and provide the basis for common understanding of product characteristics for both buyers and sellers. Their use is voluntary.

Technical Notes. This series consists of communications and reports (covering both other-agency and NBS-sponsored work) of limited or transitory interest.

Federal Information Processing Standards Publications. This series is the official publication within the Federal Government for information on standards adopted and promulgated under the Public Law 89–306, and Bureau of the Budget Circular A–86 entitled, Standardization of Data Elements and Codes in Data Systems.

Consumer Information Series. Practical information, based on NBS research and experience, covering areas of interest to the consumer. Easily understandable language and illustrations provide useful background knowledge for shopping in today's technological marketplace.